AFRL-DE-PS-
TP-2006-1017

AFRL-DE-PS-
TP-2006-1017

PLIF FLOW VISUALIZATION OF A SUPERSONIC COIL NOZZLE (POSTPRINT)

Carrie A. Noren et al.

16 October 2006

Technical Paper

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
16-10-2006	Technical Paper	01-10-2003 – 01-06-2005

4. TITLE AND SUBTITLE: **PLIF FLOW VISUALIZATION OF A SUPERSONIC INJECTION COIL NOZZLE (Postprint)**

5a. CONTRACT NUMBER: In-House (DF299896)

5b. GRANT NUMBER:

5c. PROGRAM ELEMENT NUMBER:

5d. PROJECT NUMBER: 4866

5e. TASK NUMBER: LB

5f. WORK UNIT NUMBER: 11

6. AUTHOR(S)

Carrie A. Noren*, Gretchen Gothschopf, Ty Perschbacher, Timothy J. Madden, Gordon D. Hager, C. Randall Truman*, and Peter V. Vorobieff*

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

AFRL/DELC
3550 Aberdeen Ave SE
Air Force Materiel Command
Kirtland AFB, NM 87117-5776

*University of New Mexico
Dept. of Mechanical Engineering
Schooles Hall, Room 102
Albuquerque, NM 87117-0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
3550 Aberdeen Ave SE
Kirtland AFB, NM 87117-5776

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/DELC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-DE-PS-TP-2006-1017

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution is Unlimited

13. SUPPLEMENTARY NOTES Published in 36th AIAA Plasmadynamics and Lasers Conference, June 2005, Toronto, Ontario Canada, by American Institute of Aeronautics and Astronautics (AIAA). GOVERNMENT PURPOSE RIGHTS.

14. ABSTRACT This paper describes Planar Laser-Induced Fluorescence (PLIF) flow visualization of a supersonic nozzle with supersonic injection. The nozzle simulates Chemical Oxygen Iodine Laser (COIL) flow conditions with non-reacting, cold flows, where the injected flow was seeded with iodine. A laser sheet near 565nm excited the iodine, and the fluorescence was imaged with a gated, CCD camera. Spanwise and steamwise images were taken, where the relative concentration of the injected to primary flow, turbulent structures, and penetration distance of the injected flow were identified. These images qualitatively revealed a lack of mixing of the secondary (injected) and primary flows at the centerline of the nozzle, even far downstream of the throat. Quantitative data of the penetration of the secondary flow, with varying primary to secondary flow rate ratios, helped identify the shallow angle of the injectors as an inhibiter of secondary penetration even at relatively low primary flow rates. From the PLIF results, this nozzle is characterized as a poor mixer and would not be recommended as a nozzle that produces a well-mixed medium, as required with chemical lasers. This work precedes a project that will use PLIF results to design a well-mixed supersonic nozzle with supersonic injection. The results will be compared to and enable validation of computational fluid dynamics (CFD) predictions of the designed nozzle.

15. SUBJECT TERMS
Supersonic, PLIF, COIL, injector, iodine, mixedness

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	SAR	9	Slav Peytchev
					19b. TELEPHONE NUMBER *(include area code)*

CLEARED
FOR PUBLIC RELEASE
AFRL/DEO-PA
22 MAR 05

PLIF Flow Visualization of a Supersonic Injection COIL Nozzle

Carrie A. Noren*
Department of Mechanical Engineering, University of New Mexico, Albuquerque, NM, 87131
Air Force Research Laboratory, Directed Energy Directorate, Kirtland AFB, NM, 87117

Gretchen Rothschopf†, Ty Perschbacher‡, Timothy J. Madden§, and Gordon D. Hager**
Air Force Research Laboratory, Directed Energy Directorate, Kirtland AFB, NM, 87117

and

C. Randall Truman†† and Peter V. Vorobieff‡‡
Department of Mechanical Engineering, University of New Mexico, Albuquerque, NM, 87131

This paper describes PLIF flow visualization of a supersonic nozzle with supersonic injection. The nozzle simulates COIL flow conditions with non-reacting, cold flows, where the injected flow was seeded with iodine. A laser sheet near 565nm excited the iodine, and the fluorescence was captured with a gated CCD camera. Spanwise and streamwise images were taken, where the relative concentration of the injected to primary flow, turbulent structures, and penetration distance of the injected flow can be identified.

I. Introduction

Current Chemical Oxygen Iodine Lasers (COIL), to a large extent, employ supersonic nozzles in which iodine and carrier helium are injected into the Singlet Oxygen Generator (SOG) stream upstream of the nozzle throat, in the subsonic region. Designs in which iodine is injected in the supersonic region of the nozzle[1,2,3,4,5] have the potential to provide improved performance. Injecting the iodine and carrier helium downstream of the nozzle throat decouples this flow from the SOG, allowing changes to be made to the injected mass flow without affecting the pressure upstream in the flow from the SOG. When injected into the subsonic region, the iodine and carrier helium are approximately 17-20% of the SOG's molar flow. By injecting the iodine and carrier helium into the supersonic region, the pressure is decreased by 17-20%, which increases the velocity and decreases the partial pressure of $O_2(^1\Delta)$. A lower partial pressure and a greater velocity decreases the time it takes to transport $O_2(^1\Delta)$ downstream of the throat, enabling more lasing farther downstream the nozzle. Also, because of the decrease in the $O_2(^1\Delta)$ transport time, the loss of $O_2(^1\Delta)$ is reduced in the SOG system.

Scientists have been able to study the fluid mechanics of COIL numerically and experimentally. Numerical studies have been performed on chemical lasers with iodine injection in the subsonic region of the nozzle[6,7,8,9,10] and in the supersonic region.[5] This aids in the understanding of the mixing phenomena in the fluid-dynamic flowfields. Planar Laser-Induced Fluorescence (PLIF), a non-intrusive method to image the flowfield, has been used to study the fluid mechanics of a COIL nozzle with iodine injection in the subsonic region.[11,12]

Experimental studies have been performed on transverse jets in supersonic crossflow cases.[13,14] Although the gases used do not simulate COIL, the results are important because they give relationships between the momentum

* Cooperative Graduate Research Student, AIAA Member.
† Research Scientist.
‡ Director of Operations.
§ Research Scientist, AIAA Member.
** Senior Research Scientist.
†† Professor of Mechanical Engineering, AIAA Associate Fellow.
‡‡ Assistant Professor of Mechanical Engineering.

AFRL/DE 05-107

of the jets and crossflow. This work aids in the understanding of injection penetration into a supersonic region and the factors that affect penetration distance and mixedness of the two flows.

In this study, the flowfield of a non-reacting, cold-flow, supersonic nozzle with supersonic injection was imaged with PLIF. The nozzle studied has mass flow characteristics applicable to COIL. This study was done to demonstrate that PLIF could be used to study fluid mechanic mixing in supersonic nozzles with supersonic injection. With visualization of the injected flow, one can identify turbulent structures, penetration distance of the injected (secondary) flow into the primary flow, and relative concentration of the secondary to primary flows. PLIF results may also be a tool to validate computational results and can be used to aid in the design of a well-mixed nozzle.

II. Experimental Setup

The PLIF system is used to qualitatively and quantitatively measure the fluid mechanic mixing in the flow. This system consists of an Nd:YAG laser that pumps a tunable dye laser. The dye laser is then used to excite the injected iodine molecules to cause fluorescence. This fluorescence is imaged with a gated CCD camera. Figure 1 displays a schematic of the PLIF system. The YAG laser operates at the second harmonic (532nm), with a 10Hz pulse rate and an 8- to 10-second pulse width. The output of the YAG laser is turned by two dichroic mirrors (425-675nm) into the dye laser. The tunable dye laser, with Rhodamine 6G as the dye, has a 559 to 576nm range with a peak at 566nm. Maximum iodine fluorescence occurs at ~565nm, which makes Rhodamine 6G ideal for this application. The beam from the dye laser (at 25mJ) is turned, using a BK7 prism, into a series of three lenses to collimate and expand the beam into a rectangular sheet with minimal thickness (~1-2mm). The three lenses include one spherical and two cylindrical lenses.

Once collimated and expanded, the laser sheet is directed into the nozzle through a Lexan wall. The power of the laser is reduced to 25mJ so as to not burn the Lexan walls. The laser sheet passes through the flow, exciting the iodine in the injected flow to cause fluorescence. This fluorescence is captured with a gated CCD camera. The camera has 512 x 512 pixels and is gated at 100ns. The laser sheet was arranged to pass through the nozzle flow at three different angles. The camera images the flow perpendicular to the laser sheet for each sheet angle. Figure 1 displays the sheet going through the nozzle 135° to the flow, with the camera aimed perpendicular to the laser sheet (an oblique view). Figure 2a is a schematic of the laser sheet 180° to the flow, giving a streamwise view. Figure 2b displays the laser sheet 90° to the flow, giving a spanwise view of the flow.

The nozzle is designed for a primary flow of Mach 2.5. The top and bottom contours of the nozzle are identical, each with two rows of supersonic injectors. There are three injectors in the first row and 4 injectors in the second row. Each injector has a Mach number of 3, with injection angles of 30° and 20° for the first and second rows, respectively. Figure 3 is a schematic of the injector layout. The primary flow consists of nitrogen at 88mmol/s and helium at 350mm/s. The secondary mass flow, from all fourteen injectors, is iodine at ~1mmol/s and helium at 40mmol/s. The mass flow of iodine was measured using the transmittance of an Argon-Ion laser beam (488nm) through the flow of helium and iodine.[15]

III. Results

To measure the mixing behavior of this nozzle, single-shot images were captured with different perspectives (oblique, streamwise, and spanwise). The intensity in the images is proportional to the concentration of iodine in the injected flow. Figure 4 displays oblique views (see Fig. 1) of the flow just downstream and much farther downstream of the injectors. If the right hand side of the image was tilted into the page at an angle of 45°, then the flow would be from left to right. Figure 4a is the image of the flow immediately downstream of the injectors. In this image, vortices are apparent along the upper and lower walls. It is also observed that the secondary flow does not mix into the primary flow at the centerline of the nozzle. There is a substantial region of the flow that is absent of molecular iodine, where there is a lack of fluorescence. As seen farther downstream in Fig. 4b, the turbulent structures are much larger. There is greater mixing than in the flow just downstream of the injectors, yet there still is no penetration into the centerline of the nozzle.

A streamwise view of the flow is depicted in Fig. 5. In these images, the flow is from left to right. Figure 5a depicts the raw image as taken from the camera, whereas Fig. 5b is a color-enhanced version of the raw image. The pixels with little or no intensity (where there is minimal iodine) are pictured white and the pixels with intensity values depicting high iodine concentration are pictured as orange. This is similar to what is seen by the eye.

A spanwise view of the flow is shown in Fig. 6. As in Fig. 5, Fig. 6a is the raw camera image and Fig. 6b is a color-enhanced image. In this view, the flow is coming out of the page. There is reflection of the fluorescence off the top and bottom walls of the nozzle. The reflection line is displayed as a dashed line in the image. In this image,

turbulent structures (vortices) can be identified, as well as the general mixing of the secondary and primary flows. As shown in Figs. 4 and 5, there is minimal penetration into the centerline of the nozzle.

To study the penetration of this supersonic nozzle, images were taken over a range of secondary to primary flow rate ratios. This was done with the idea that an increase in the secondary to primary flow rate ratio would increase the secondary flow penetration toward the centerline of the nozzle. Penetration values were measured over an ensemble of ten images. Each image was normalized and a threshold was set at 3%. Any pixel with intensity over 3% was considered a pixel penetrated with the secondary flow. Penetration was determined by the ratio of 'penetrated' pixels to the overall pixel count for the image. Figure 7 is a plot of the secondary flow penetration versus the secondary to primary flow rate ratio. It can be seen that the penetration increases with increasing flow rate ratio. This is intuitive because as the secondary flow rate increases (or the primary flow rate decreases), the secondary flow should overcome the momentum of the crossflow to reach closer to the centerline of the nozzle. However, if Fig. 7 were extrapolated beyond a flow rate ratio of 0.85, one could determine that the secondary flow would never penetrate into the centerline. This is because of the shallow angle of the injectors (20°-30°) and the expanding nozzle walls. Even with no primary flow, the injected flow would hug the walls of this nozzle.

IV. Conclusion

This experiment revealed the capabilities PLIF lends the fluid mechanics field to study flow interactions of nozzles with supersonic injection. Here, turbulent structures were identified along with general penetration characteristics. With this specific nozzle, PLIF results identified a lack of mixing between the primary and secondary flows. Future work includes designing injectors of a nozzle that will penetrate into the centerline and produce a well-mixed medium of secondary and primary flows. The PLIF results will also be compared to and enable validation of computational fluid dynamic (CFD) predictions. This is important for future designs of supersonic nozzles with supersonic injection, where the fluid mechanic modeling is expensive and time-consuming.

For the next run of experiments, a camera with higher resolution and less noise will be used. Instead of the Princeton Instruments 512 x 512 front-illuminated CCD, an Alta U47 back-illuminated CCD array with 1024 x 1024 pixels will be used. The quantum efficiency of a front-illuminated array is approximately 65%, whereas the quantum efficiency of a back-illuminated array is 90%. This difference in quantum efficiency will greatly reduce the noise in the images.

References

[1] Hager G. D., Watkins, L. J., Meyer, R. K., Johnson, D. E., Bean, L. J., and Loverro, D. L., "A Supersonic Chemical Oxygen-Iodine Laser," AFWL TR-87-45, 1987.

[2] Nikolaev, V. D., Zagidullin, M.V., Svistun, M. I., Anderson, B. T., Tate, R.F., and Hager, G. D., "Results of Small-Signal Gain Measurements on a Supersonic Chemical Oxygen Iodine Laser with an Advanced Nozzle Bank," *IEEE Journal of Quantum Electronics*, Vol. 38, 2002, pp. 421-428.

[3] Zagidullin, M. V., Nikolaev, V. D., and Hager, G. D., "High Gain, High Pressure, Highly Efficient COIL," *High-Power Laser Ablation V, Proceedings of the SPIE*, Paper 5448-169, Vol. 5448, C. R. Phipps, ed., 2004, pp. 1139-1149.

[4] Barmashenko, B., Rybalkin, V., Katz, A., and Rosenwalks, S., "Paramentric study of the Ben-Gurion University Efficient Supersonic Chemical Oxygen-Iodine Laser," *High-Power Laser Ablation V, Proceedings of the SPIE*, Vol. 5448, No. 1, C. R. Phipps, ed., 2004, pp. 282-293.

[5] Madden, T. J., Hager, G. D., Lampson, A. I., and Crowell, P. G., "An Investigation of Supersonic Mixing Mechanisms for the Chemical Oxygen-Iodine Laser (COIL)," *30th Plasmadynamics and Lasers Conference*, AIAA 99-3429, Jun. 1999.

[6] Madden, T. J. and Miller, J. H., "Simulation of Flow Unsteadiness in Chemical Flowfields," AIAA Paper 2004-0805.

[7] Miller, J. H., Shang, J. S. Tomaro, R. F., and Strang, W. Z., "Computation of Compressible Flows Through a Chemical Laser Device with Crossflow Injection," *Journal of Propulsion and Power*, Vol. 17, No. 4, Jul.-Aug. 2001, pp. 836-844.

[8] Miller, J. H. and Shang, J. S., "Parallel Computation of Chemical Oxygen/Iodine Laser Flowfields" *32nd Plasmadynamics and Lasers Conference*, AIAA 2001-2869, Jun. 2001.

[9] Madden, T. J. and Solomon, W. C., "A Detailed Comparison of a Computational Fluid Dynamic Simulation and a Laboratory Experiment for a COIL Laser, " *28th Plasmadynamics and Lasers Conference*, AIAA 97-2387, June 1997.

[10] Masuda, W., Hishida, M., Hirooka, S. Azami, N., and Yamada, H., "Three-Dimensional Mixing/Reacting Zone Structure in a Supersonic Flow Chemical Oxygen-Iodine Laser, " *JSME International Journal, Series B—Fluids and Thermal Engineering*, Vol. 40, No. 2, 1997, pp. 209-215.

[11] Rapagnani, N. L. and Davis, S. J., "Laser-Induced I_2 Fluorescence Measurements in a Chemical Laser Flowfield," *AIAA Journal*, Vol. 17, No. 12, 1979, pp. 1402-1404.

[12] Muruganandam, R. M., Lakshmi, S., Ramesh, A. A., Viswamurthy, S. R., Sujith, R. I., and Sivaram, B. M., "Mixing of Transversely Injected Jets into a Crossflow Under Low-Density Conditions," *AIAA Journal*, Vol. 40, No. 7, Jul. 2002, pp. 1388-1394.
[13] Gruber, M. R., Nejad, A. S., Chen, T. H., and Dutton, J. C., "Transverse Injection from Circular and Elliptic Nozzles into a Supersonic Crossflow," Journal of Propulsion and Power, Vol. 16, No. 3, May-June, 2000, pp. 449-457.
[14] Lee, M. P., McMillin, B. K., Palmer, J. L., and Hanson, R. K., "Planar Fluorescence Imaging of a Transverse Jet in a Supersonic Crossflow," *Journal of Propulsion and Power*, Vol. 8, No. 4, Jul.-Aug. 1992, pp. 729-735.
[15] Davis, S. J., U.S. Patent 4,467,474, "Halogen mass flow rate detection system," 21 Aug. 1984.

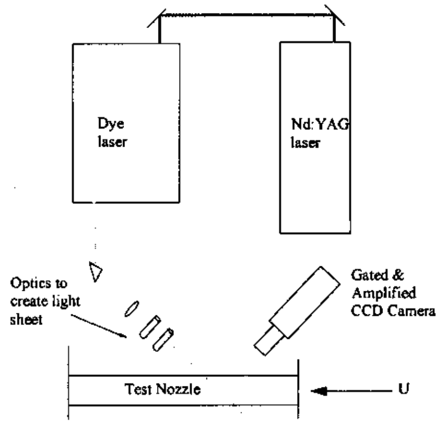


Figure 1. A schematic of the PLIF system, with the camera and laser sheet set up for an oblique view of the flow.

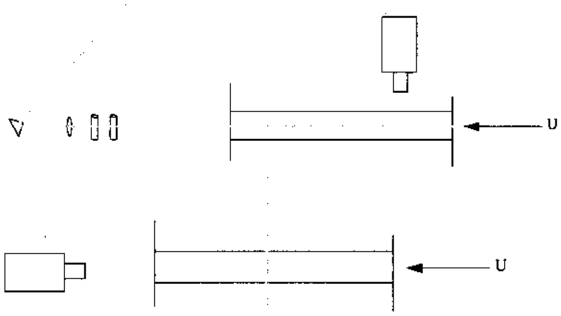


Figure 2. Schematics of the laser sheet at a) 180° and b) 90° to the primary flow.

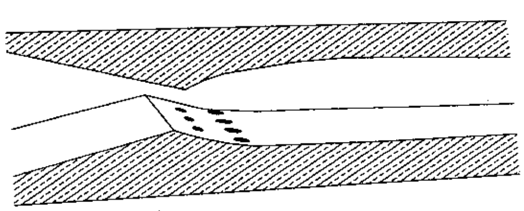
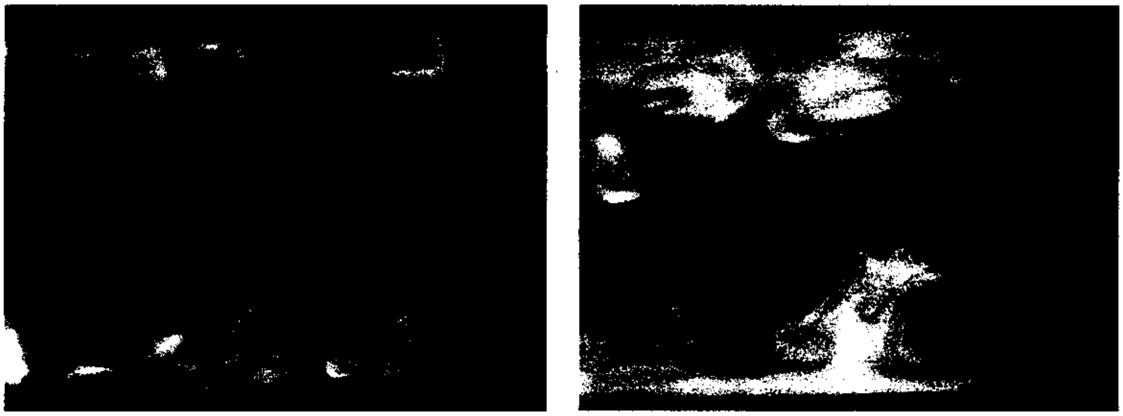
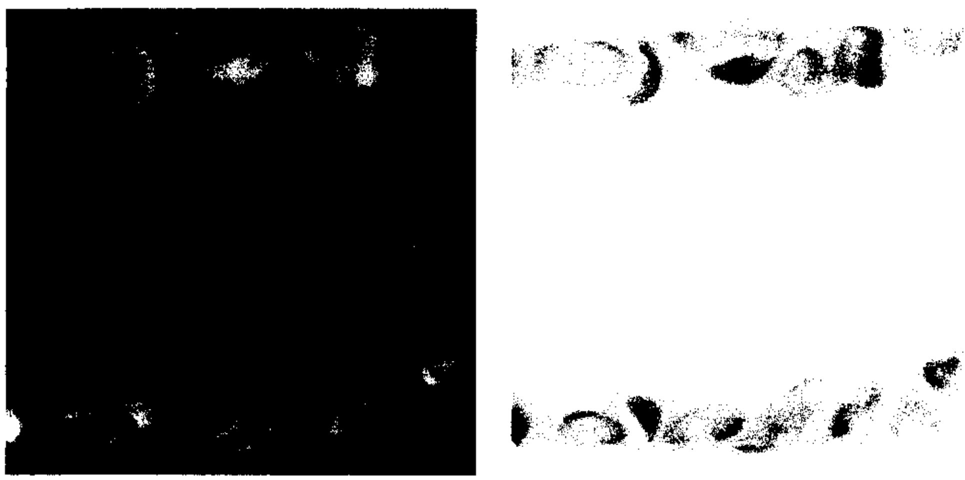


Figure 3. Schematic of the nozzle with the injectors shown on the bottom wall, flow is from left to right.



a) b)

Figure 4. Oblique view of the nozzle fluid flow where a) is immediately downstream of the injectors and b) is farther downstream.



a) b)

Figure 5. Streamwise view of the flow just downstream of the injectors where a) is the raw image from the camera and b) is a color-enhanced version of a).

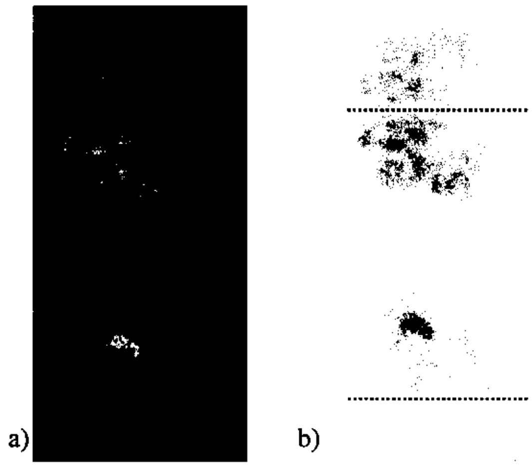


Figure 6. Spanwise view of the flow, with the laser sheet just downstream of the injectors where a) is the camera raw image and b) is the color-enhanced version of a).

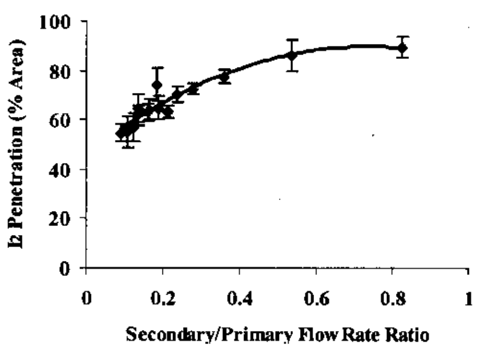


Figure 7. Secondary flow penetration versus the secondary to primary flow rate ratio.